New 20-kW CW Transmitter for NASA's Deep Space Network[1][2]

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Abstract—A 20-kW S- and X-Band transmitter was developed for NASA's Deep Space Network (DSN) 70-m antennas. The transmitter consists of two separate high-power amplifiers and common supporting assemblies. The new design includes innovations in control and monitoring that simplify the overall transmitter implementation and substantially improve its maintainability.

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1. INTRODUCTION

Due to the implementation of equipment in 70-m antennas, the major transmitter assemblies are separated by long distances. For example, power amplifiers (PAs) are placed near the antenna feed, but because of limited space and maintenance considerations, the High-Voltage Power Supply (HVPS) cabinet is located in the antenna pedestal at ground level. The Signal Processing Center (SPC) is usually located several hundred feet from the antenna pedestal. This dispersion of hardware over long distances creates challenges in transmitter design.

Previous DSN transmitter implementations employed centralized control using relay logic and analog meters located in the high-voltage (beam) power supply cabinet. This architecture required hundreds of hard-wired connections to sensors and instruments that were located up to 500 feet away. A custom interface assembly converted analog data and status indications to an RS-422 interface for reporting to, or for control from, the subsystem computer controller (in the SPC). The main disadvantages of this design were:

- need for a large amount and cost of custom-made cabling,
- need for custom circuitry for relay logic and analog meters,
- need for a custom computer interface assembly,
- considerable time for hardware maintenance and repairs.

Also, because the transmitters were designed many years ago, replacement parts have become obsolete or difficult to obtain. New safety regulations require all internal antenna cables to be plenum-rated which makes long custom-built cables more expensive and available from very few vendors.

The new design replaces most of the relay logic with a digital controller that communicates with instruments in each PA over an Ethernet LAN. The suite of instruments consists of Commercial Off-the-Shelf (COTS) power meters and data acquisition units that monitor operation of the transmitter. Because of the need to shut off the high-voltage (beam) power supply within milliseconds of detecting a fault, a hard-wired interlock "chain" is implemented as in previous transmitters; however, the interlock status is now monitored by a data acquisition unit located in the power amplifier and reported to the controller. The use of COTS instruments results in having a more stable and robust measurement system which can be periodically removed in the field and sent for factory calibration.

A compact and simple real-time program written in Ada is used to control the transmitter. The user interface, needed only for maintenance, is provided through a Dynamic Linked Library (DLL) that interfaces with HP-VEE software to provide a graphical user interface as well as an interface for a socket connection to other programs which can independently monitor computer operation. When the sockets interface and other upgrades (such as automated saturation and power-leveling algorithms) are fully evolved

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and implemented, complete transmitter management can be reduced to a high-voltage cable, Ethernet link, and a single pair of wires for the interlock function, resulting in substantial savings in cabling, connectors, and complexity.

For a smooth transition from the old transmitters to the new ones, the transmitters delivered to 70 m antennas retain most of the previously-designed cable system, as well as an old-style analog control panels and legacy computer interface. The complete transition to a digitally-controlled transmitter requires concurrence by DSN operations and the uplink subsystem to which the transmitter belongs.

2. TRANSMITTER FUNCTIONAL DESCRIPTION

Block-diagram and major assemblies

The newly implemented transmitter delivers a minimum of 20-kW Continuous Wave (CW) power to the 70-m uplink in the frequency range 7145–7190 MHz (X-band) or 2110–2120 MHz (S-Band). (The modulated drive signal is provided by a special exciter and is not covered in this article). Design features of the transmitter were influenced by several factors: experience with operation of earlier DSN transmitters, very strict requirements imposed on output power stability (0.1 dB for 12 H), low phase noise, low level of amplitude modulation, and low radiation beyond the assigned bandwidth (EMI). The simplified transmitter block-diagram is shown in Figure 1.

The transmitter consists of several major assemblies which provide various functions for the transmitter and are located in different areas of the 70-m communication complex as indicated in Figure 2.

The signal processing center contains an analog control panel which provides remote monitoring and control of the transmitter during operation or maintenance. An Ethernet HUB has been added to create a connection point for the laptop computer which can provide a maintenance display with more data than is available on the analog control panel.

The power house contains a Motor-Generator (MG) which converts facilities-supplied 60-Hz power to the regulated 0–480 Vac, 420-Hz, 3-phase power, which is used as a primary source for the HVPS (beam supply). An MG controller, co-located with the MG, provides control and protective circuits for the MG.

The antenna pedestal contains the HVPS, a new Transmitter Control Assembly (TCA), and a Warning Light Controller. The HVPS provides highly-regulated power (20 kV at 3–4 A) for the klystron [1, 2]. As in the traditional transmitter implementation, it also provides controls, interlock logic and indication, the internal traditional transmitter interface, and the interface for remote control by

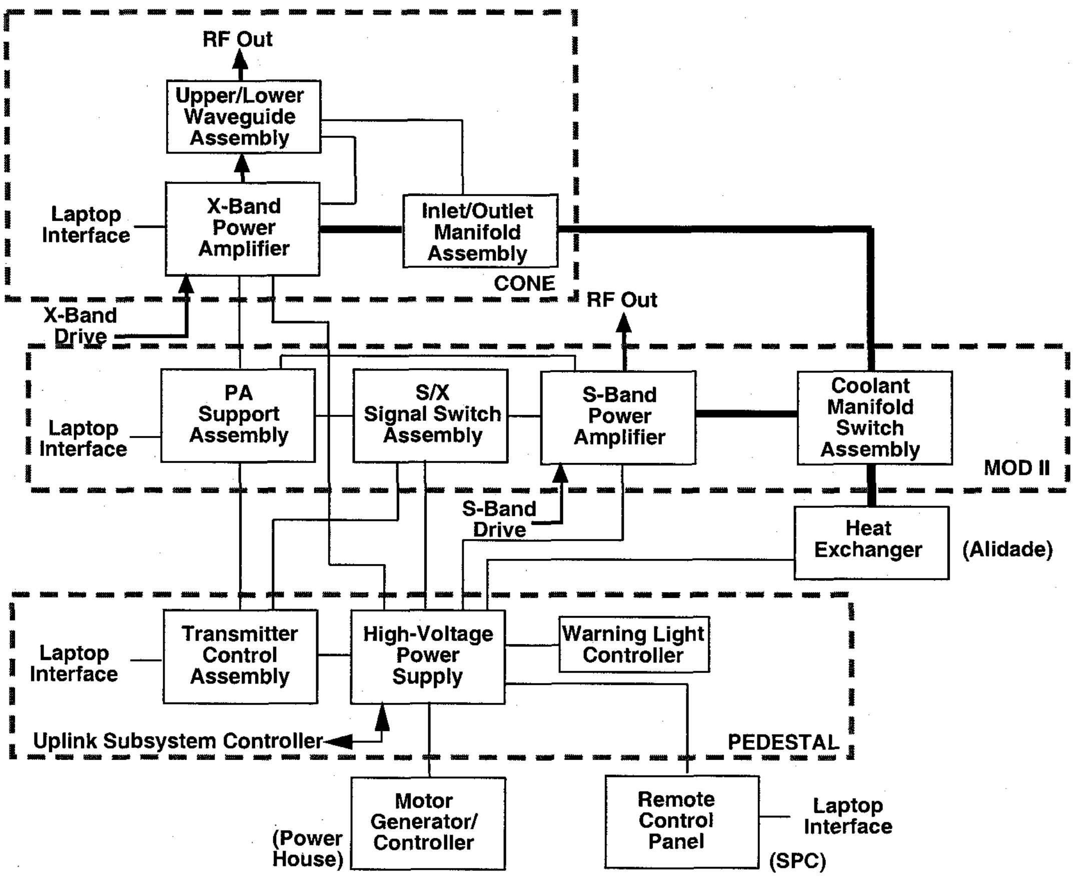

Figure 1. Block Diagram of the DSN 70-m Uplink Transmitter

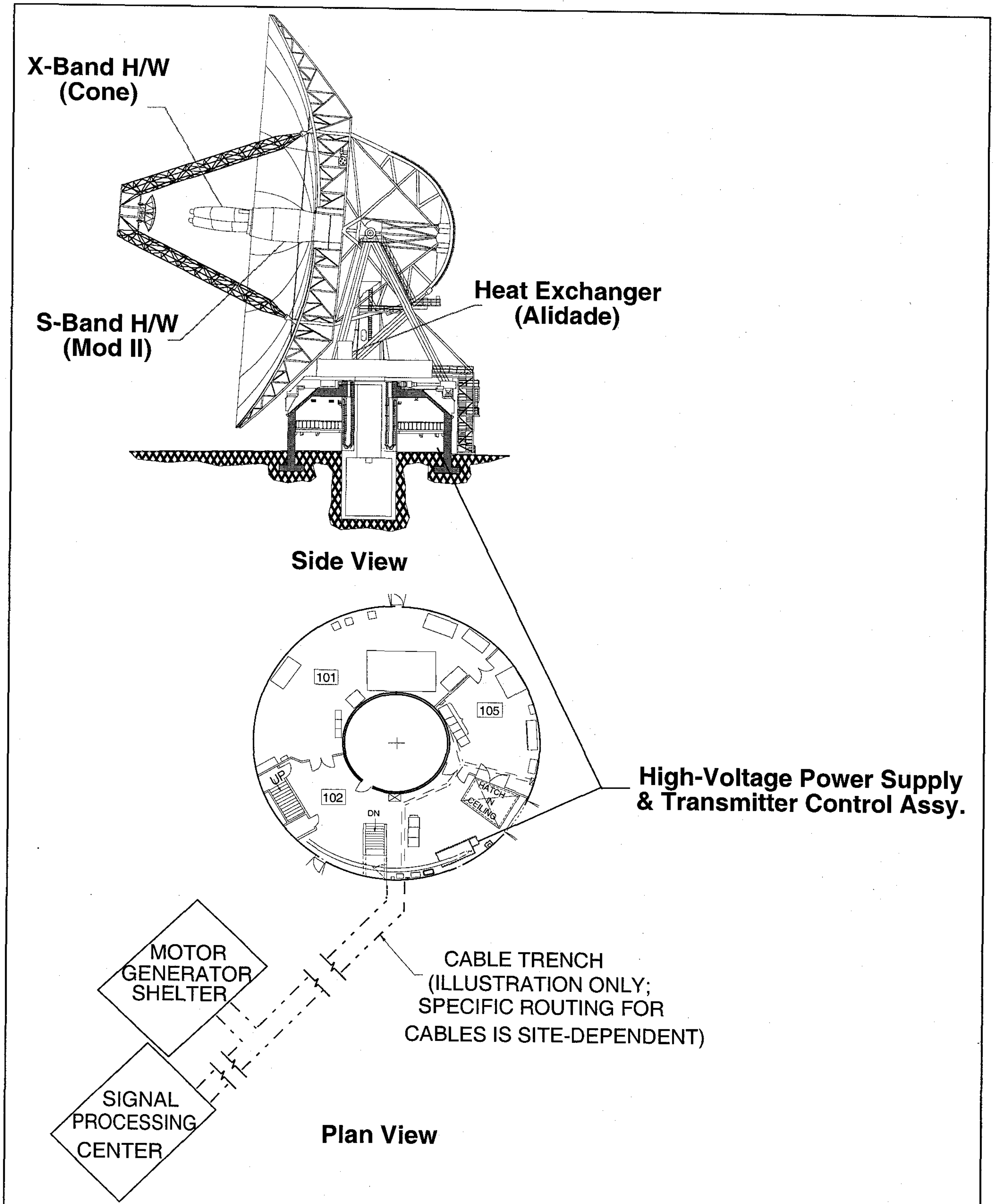

Figure 2. Physical Locations of Transmitter Assemblies

the uplink subsystem controller. The warning light controller activates warning lights on the antenna to warn personnel that high-voltage is on or that the transmitter is radiating.

The TCA provides fully computerized transmitter control with several different maintenance screens on its display and collects and records transmitter performance data. Calibration files which control the operation of the COTS instruments are maintained on the TCA computer. The TCA also provides the traditional multi-wire interface as well as the LAN interface between transmitter assemblies. For compatibility with the existing uplink subsystem controller, the TCA is connected so its existence is transparent. The only exception to being transparent is that the TCA reports its own status to the controller.

The heat exchanger, located on the alidade deck, supplies temperature-regulated cooled water to the transmitter heat loads. The heat exchanger is a liquid-to-air type and is capable of dissipating 75-kW while regulating with ±1 deg C over a wide ambient temperature range. The heat exchanger uses pure de-ionized water to eliminate the potential for creating hazardous glycol waste as well as to eliminate the need for glycol-related correction factors in calorimetric calculations.

The 70m antenna design places the feed aperture at the focal circle of the main reflector. Because this point is about 60 feet above the reflector, a cylindrical hub structure is used to support the feeds which are housed in "cones" about 20 feet high and about 10 feet in diameter. The S-Band transmitters are located approximately mid-way in the hub structure ("Module II" or "Mod II") supporting the cones because the transmission loss in S-Band waveguide is relatively low. The Mod II area contains four assemblies, a 20 kW S-Band PA, a PA Support Assembly (PASA), and two switching assemblies, one for signals and another for cooling water.

The S-Band 20 kW power amplifier provides amplification of the S-Band exciter signal (9±3 dBm) to a level of +53 dBm to +74 dBm, as required by Operations. The PA was completely refurbished and provided with COTS power meters and a data acquisition unit.

The PASA provides some of the X-Band PA functions which can be located outside of the space-constrained cone. These include 115 Vac power control, GPIB-controlled primary filament power, and 28 Vdc for different sensors. In addition, for S-Band, the PASA provides the GPIB interface for its instruments, and 115 Vac power control. The PASA contains an Ethernet HUB as well as the traditional cable interface to the X-Band PA.

The X/S Signal Switching assembly switches signals between X- and S-Band PAs, thus eliminating the need for an additional set of 500-ft signal cables from HVPS and TCA to the PAs. The Coolant Manifold Switching assembly switches water flow between X- and S-Band PAs.

The X-Band PA with its associated water manifolds and waveguide assemblies are located in one of the feedcones. The X-Band PA provides amplification of the X-Band exciter signal (9±1 dBm) to a level of +53 dBm to +74 dBm, as required by Operations. The frequency range is 7145–7190 MHz and can be manually retuned to the High Earth Orbiter (HEO) band (7190-7235 MHz) if required.

The Inlet Coolant manifold distributes cooling water from the heat exchanger to the different heat loads in the PA and provides instrumentation for water flow control and measurement. The Outlet Coolant manifold collects water from the PA heat loads and directs it to the heat exchanger. Sensors on the manifold provide transmitter protection water flow interlocks for each heat load, collector coolant overtemperature interlock, and collector coolant underpressure interlock.

The waveguide assemblies suppress harmonics, protect the transmitter from high reflected power, and transport RF power to the microwave subsystem for radiation into the antenna. They also provide RF sensors and a water load to support transmitter operation and testing.

3. INNOVATIONS

Localized Interlock Monitoring

The traditional interlock implementation in DSN transmitters used switches in the PA to activate relays in the HVPS to control whether or not the high-voltage beam could be activated, i.e., "Beam Ready" (Figure 3).

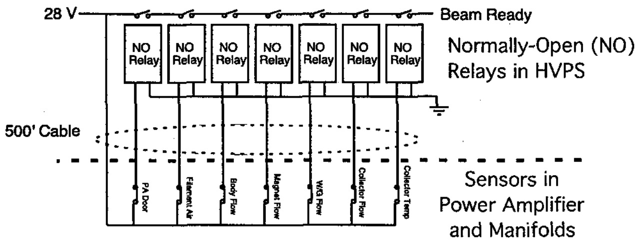

Figure 3. Simplified Traditional Schematic for Interlock

For safety reasons, the newly implemented protection circuitry still maintains a hard-wired interlock chain, but reports interlock status independently. Most of the interlock contacts (located in the PA and manifolds) are connected in series with the transmitter shutdown circuit, creating the "interlock string" that turns off high voltage if any of the contacts are open. The information about contact status is collected by the COTS data acquisition unit, which outputs them in GPIB format. The data is then converted to TCP/IP format and reported to the embedded computer, which controls the relays located in the HVPS cabinet. Fundamental changes to interlock management are shown in Figure 4. The new protection circuitry requires only two wires and one Ethernet link to perform the same functions as the traditional circuitry.

RF power measurement

Each PA is a two-stage amplifier. The first stage is a solid-state buffer amplifier which can provide adequate output to drive the klystron tube in the second stage. For RF power measurement, the transmitter is equipped with two dual-channel digital power meters and four power sensors. Two sensors monitor buffer amplifier input and output power. The other two power sensors measure forward (or output) power and power reflected from the antenna by means of a dual-directional coupler at the output of the transmitter.

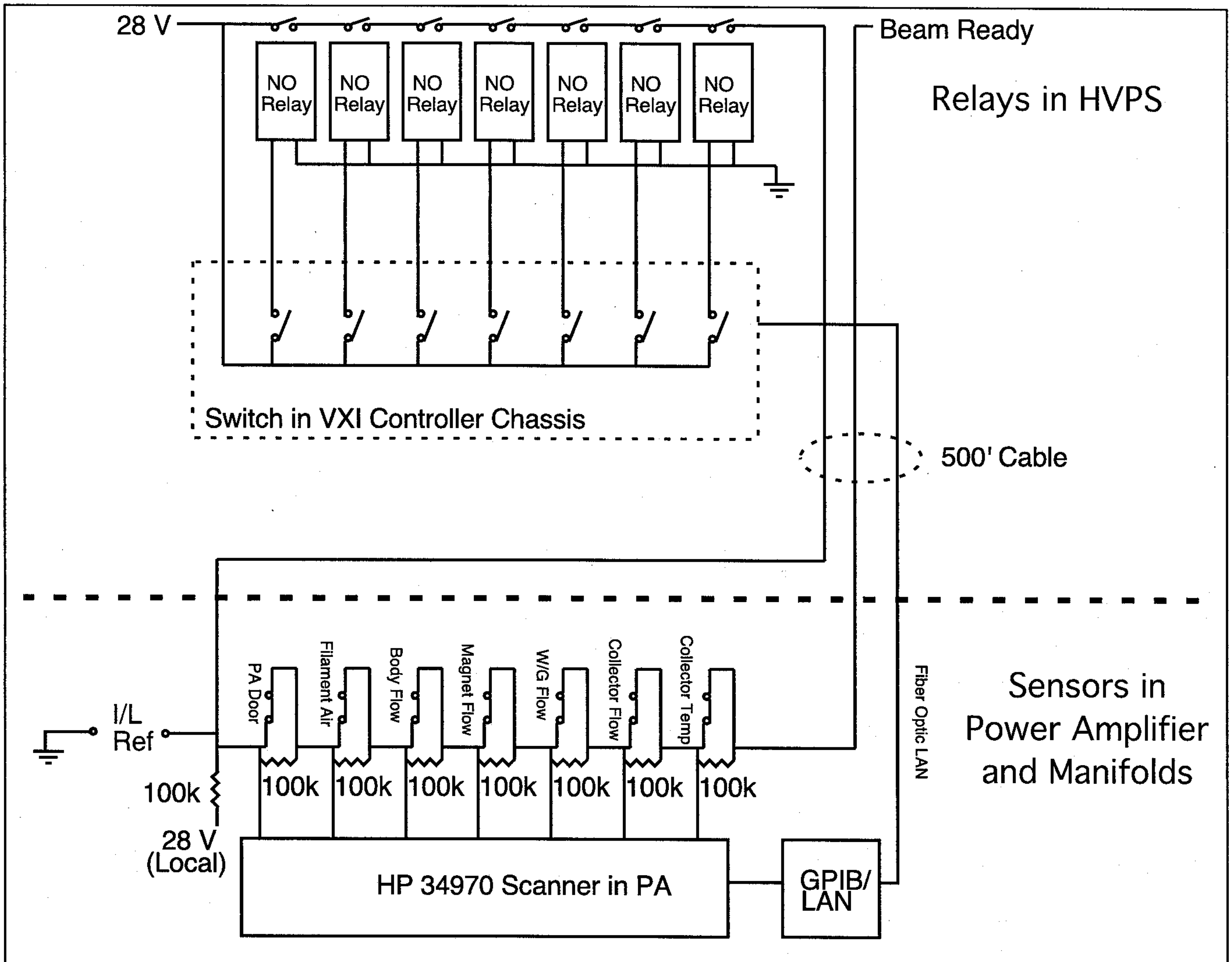

Figure 4. Simplified New Schematic for Interlocks

At transmitter startup, offsets for each channel are loaded into the power meters, so that each meter displays direct power readings. The offsets are determined during transmitter calibration and are a function of the coupling factors of the couplers used and other measured circuit losses. During operation, power meter readings are taken four times per second. Power meters are controlled via a GPIB interface, and error conditions are checked (and logged if present) every 20 seconds.

The power meters have a built-in calibrator, so they can be used to make accurate relative measurements within the transmitter to determine losses when changing such transmitter hardware as RF coaxial cables, RF detectors, pads, coaxial couplers, etc. This internal calibration reference greatly improves transmitter maintainability compared to the old transmitter implementations.

Another innovation used for transmitter self-test and calibration is a built-in high-power calorimeter [3]. The internal water load, connected to the waveguide assembly via a Radiate/Load switch, is equipped with two precise RTDs for measuring the inlet and outlet water temperature. The water cooling circuit also has a very accurate turbine flowmeter, which supplies data for dissipated heat calculation. Connecting the waterload and klystron collector in series (in a coolant circuit) and measuring the collector water outlet temperature with an additional RTD allows checking the power balance and discriminating different problems with the flowmeter, RTDs, and beam voltage and current measurements by using the relation:

$$V_{beam} \times I_{beam} = P_{col} + P_{load},$$

where:

V_{beam} and I_{beam} are the beam voltage and current, respectively (data is supplied by direct measurement in the HVPS),

P_{col} and P_{load} are the power dissipated in a klystron collector and water load respectively and are calculated by the computer using flowmeter and differential temperature readings.

Data acquisition

The data acquisition assembly in each PA provides analog measurements, senses interlock contact positions (in X-

Band PA), and converts data into GPIB format. The central component of the data acquisition assembly is a commercial, rack-mounted data acquisition unit equipped with differential 20-channel multiplexers (two for X-Band PA and one for S-Band PA). For convenient field service, all wires come to the assembly connected to three-circuit terminal blocks. Additionally, 50-contact D-sub connectors are employed for convenient swapping of prewired multiplexer cards.

The unit is programmed for auto ranging, which simplifies use and eliminates data conditioners. The Data Acquisition/Switch Unit samples different signals with different rates. The rates are defined by preloaded transmitter software. The results of measurements are converted to a TCP/IP format for sending to the computer controller via the LAN/GPIB Gateway.

Transmitter controller

The controller assembly is located in the TCA's 19-inch instrumentation rack. Cabling between the HVPS and the TCA allows the HVPS cabinet to be compatible with old DSN implementations while allowing the TCA access to the signals inside the HVPS. The main part of the controller is a VXI computer, which executes custom transmitter control software and runs under Windows NT. The computer itself is integrated with a HP-based VXI cardcage chassis and five functional cards:

- 5.5-Digit Multimeter
- FET Multiplexer
- 8/16-Channel D/A Converter
- 64-Channel Switch
- 96-Channel Digital I/O Module.

The VXI bus located at the back plane of the main chassis provides internal communication with any plug-in VXI card. The interface signals come to each card via card-specific front adapters. The controller receives information about transmitter parameters in three different ways:

- A FET Multiplexer, which accepts analog signals (beam voltage, beam and body current, and drive attenuator position) and directs it to the scanning multimeter,
- A 96-channel digital I/O module (for interlock and indicator readings) and
- An Ethernet connection.

The existing traditional DSN transmitter interface operates with slowly-changing analog signals (range 0–5 V) and 28 Vdc digital signals. For compatibility with the 28 Vdc interface, external signals are directed to the I/O module via a 96-channel voltage divider (28 V to TTL level). Digital commands, several interlock relays, and interlock indicators are controlled by the 64-channel switch with nonlatching SPDT relays. Analog signals derived from the digital instruments are generated by a D/A converter, which supplies those signals to the analog meters and to the traditional interface with the uplink subsystem controller. Each signal wire is terminated at the terminal block for convenient troubleshooting.

The TCA rack also contains two external drives (CD-ROM and Jaz), an Ethernet HUB, a 17-inch color monitor, keyboard with trackball, and other auxiliary subassemblies. A 2-GB Jaz Drive is used to off-load log files and for software backups. Because the VXI computer is equipped with only a 3.5-inch floppy drive, an external CD-ROM drive is provided for loading software. All drives are located in a sliding drawer for convenient service. The Ethernet HUB is combined from commercial parts and is capable of supporting several RJ-45 ports and fiber-optic links.

Using the computer controller along with GPIB/LAN-controlled instrumentation makes future upgrades, new instrumentation, new status indicators, and protection interlocks much easier to add and configure. For example, in old transmitter implementations the Drive On indicator was controlled by a special relay that switched the visual panel indicator (and sent a 28-Vdc information signal) when a special RF detector and comparator detected that the exciter signal exceeded a predetermined level. The circuit required calibration each time hardware was replaced and was affected by temperature drift. In the new S-Band PA, only one line in the software is needed to generate the same signal. The indication level can be changed easily by changing one number in the calibration file. The circuit does not require an additional coupler, RF detector, comparator, adjusting potentiometer, or additional calibration because the data is obtained from one of the power meter channels already. Another example of hardware simplification is the elimination of a time delay relay and regulating resistor from the klystron filament circuit (X-Band PA). Time delay is calculated by computer, which also displays the expected waiting time remaining to the operator. The command for a 10% decrease in filament voltage when the beam is off is also generated by computer and is sent via LAN/GPIB to the remotely-controlled filament power supply.

Also, it is easy to provide the results of calculated or derived parameters based upon transmitter parameter measurements. An example is a new parameter, klystron gain, which is displayed at the computer control panel or the previously-mentioned Collector and Calorimetric Load Power displays which can help in troubleshooting and self-testing.

Another added capability is the ability to log transmitter performance data to a computer file. There are 15 logging parameters available for the S-Band transmitter and 40 parameters for X-Band. These data are important for troubleshooting and problem analysis, and provide the data necessary to support a continuous improvement program for the transmitter subsystems used throughout the DSN. The current version of software automatically logs most of the important parameters on a one reading per minute basis.

Transmitter Control Software

The TCA computer at startup executes a real-time program, written in Ada, called SX_MON, which controls the transmitter. It writes and reads the DLL and calls hardware input/output libraries to interact with the VXI cards and GPIB instruments. The software reads calibration files to establish the operating conditions for the transmitter and parameter files to control the parameters to be logged. There is no direct user interface. Instead, SX_MON communicates through the DLL with an HP-VEE program to produce the electronic control panel which appears on the TCA screen. In addition, a newly-implemented sockets protocol allows access to the DLL. Software in the TCA or in other computers connected via Ethernet to the TCA can access the SX_MON DLL to monitor or control the transmitter (if the correct password is supplied.) Thus, other software can provide alternate views of the transmitter operation. For example, one program has been written to capture user-defined parameters (that appear in the DLL) at a once per second rate, allowing some transient phenomena to be captured for analysis.

The real-time software produces two log files, one of which is a copy of messages generated during a single transmitter operation (typically 6–8 hours) and another is a binary file which contains the history of the parameters specified in the input parameter file. The binary file is formatted to be compatible with the COTS software MATLAB to allow easy analysis of the logged data.

Computer Control Panel

Newly implemented transmitters include a computer control panel (keeping the traditional hardwired control panel and interface untouched). The computer-simulated control panel was created using a relatively simple graphical programming language (HP-VEE). It provides not only an alternative to the analog control panel, but provides expanded functionality. The control panel is available to any computer connected to the transmitter LAN. Figure 5 shows the computer-generated main control panel.

Most parameters are displayed as simulated analog meters with additional high-precision digital readouts. The panel presents to the operator two choices to raise or lower beam voltage: numerical setting of the desired value, or timed raise/lower (operator choice of timing from 0.2 to 8 seconds). The RF power raise/lower command allows a choice of three drive power settings, including setting the

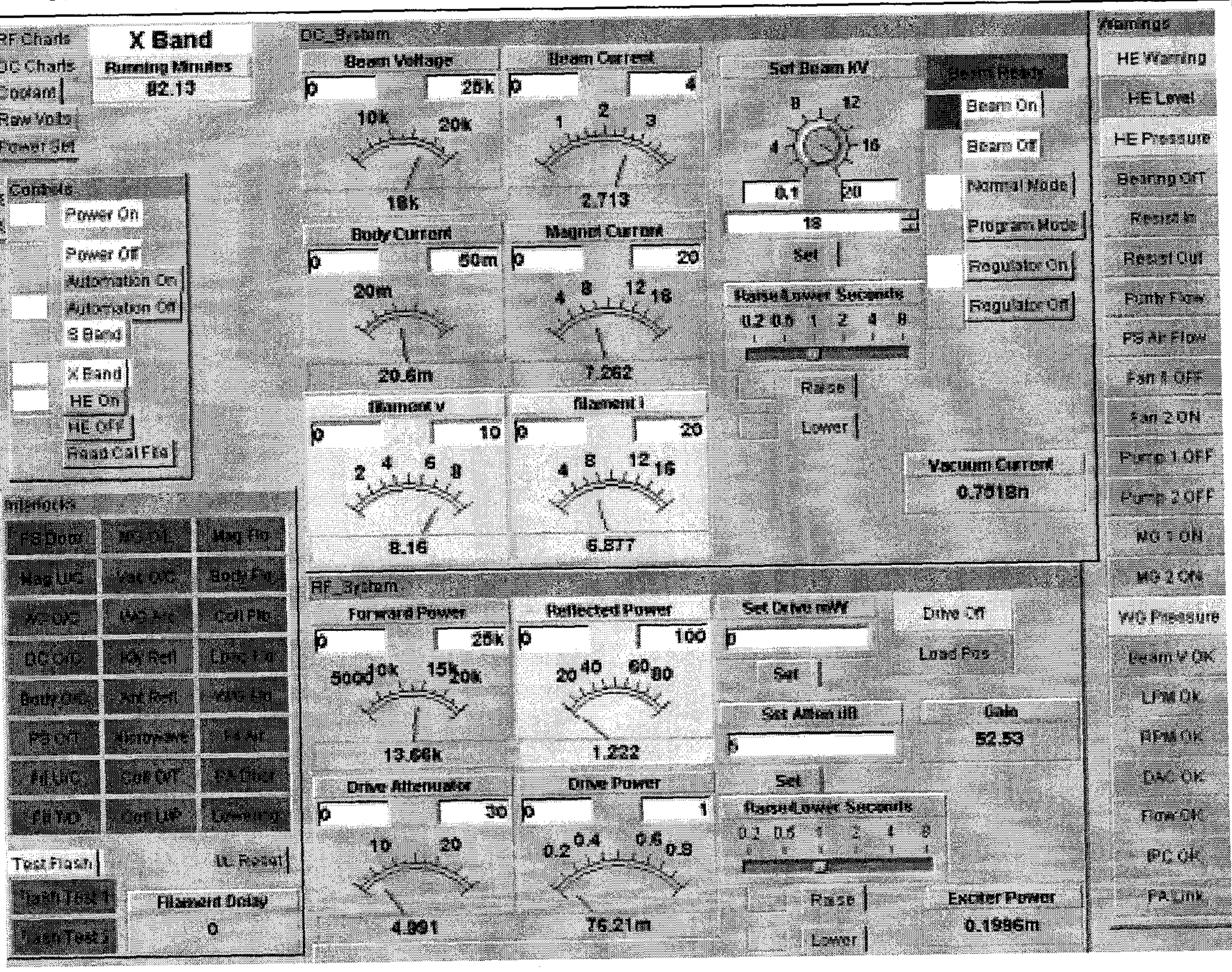

Figure 5. Computer-Generated Main Control Panel

attenuation of a remotely controlled attenuator in a buffer amplifier.

The new panel also allows the operator to control power to different assemblies in Module II and the cone via Ethernet-connected remote power switch. Calibration factors can be read and applied if any corrections were made during real time operation or during a calibration procedure. The operator can open and close additional screens and change scales in real time (and restore defaults) without interruption of transmitter operation. The additional screens provide raw data (real volts measured in interlock string, etc.), strip charts of the main RF and dc parameters, water flows, pressure, and temperature readings in the various cooling circuits.

For ease of troubleshooting, the panel includes a message column (at right). The top part of this column correlates with warnings at the analog control panel. The bottom part warns about communication problems and provides the status of different instruments. If there are no problems, messages appear on a gray background, display the device name and "OK." If a problem occurs, background appears red and, instead of "OK," "ERROR" is displayed.

4. Conclusions

A new 20-kW CW dual X- and S-Band transmitter with embedded computer controller was designed and has been implemented in two of the three 70-m DSN antennas. Use of COTS at the assembly level rather than for the entire PA results in a reusable design which can be moved from transmitter to transmitter thus lowering design and development costs when producing small quantities of each transmitter. (The DSN typically produces only three units of any given transmitter subsystem.) The COTS power meters have significantly improved power monitoring accuracy, precision, and stability. Moreover, having easily-replaceable units allows them to be factory-calibrated on a periodic basis without the need for maintenance time to perform the calibration on the antenna.

The transmitter controller has produced several benefits:

- The need for custom logic boards for each transmitter is significantly reduced.
- A sockets interface can provide operational control and maintenance to access the transmitter without the need for a custom interface unit.
- Data logging provides information to support maintenance and for long-term "continuous improvement" of the transmitter subsystem.
- The use of digitally-controlled instrumentation provides a flexible growth capability for additional functionality.

Although it is too early to verify the expectations of improved availability and reduced maintenance time for these transmitters, there is ample incentive in DSN operations to use similar equipment in other transmitter systems. The experience gained during the 70-m implementation will be used in a task to upgrade the 20 kW transmitters in the 34-m antennas as well as the 400 kW S-Band transmitters in the 70-m antennas over the next several years.

References

[1] J. Daeges and A. Silva, "Analysis and Performance of a 12-Pulse High Power Regulator," *Conf. Record 21st International Power Modulator Symposium*, Costa Mesa, CA, June 27–30, 1994, pp 156–158.

[2] A. Silva, "Spectral Analysis and Performance of a 20kW CW Uplink Transmitter," *Conf. Record 22nd International Power Modulator Symposium*, Boca Raton, FL, June 25–27, 1996, pp 104–107.

[3] R.M. Perez, B. L. Conroy, "Calorimeric Output Power Measurements on a CW 20 kW 7.16 GHz Microwave Transmitter," *IEEE Transactions of Instrumentation and Measurement*, Vol. 40, N:1, February, 1991, pp. 49–51.

Biographies

David L. Losh received the B.S. degree in physics from Case Institute of Technology, Cleveland, OH, in 1970, and the M.S. degree in computer science from University of Southern California, Los Angeles, in 1980.

In his position as a Senior Telecommunications Engineer in the Communications Ground Systems Section, he is the Engineering Manager for the 20-kW transmitters described in this paper. Previous work at the Jet Propulsion Laboratory, Pasadena, CA, includes Task Manager for a microwave-powered aircraft to provide telecommunications services to sparsely populated areas and experiment director for a phased-array coherent microwave power uplink system.

Yakov Vodonos received his BS degree in Electronics from Moscow College of Radio Equipment in 1965, MS degree in Physics and Mathematics from Moscow Engineering Physics Institute in 1971, and Ph.D. degree in Technical Sciences from Moscow Aviation Institute in 1992. In his position as a Senior RF and Microwave Engineer in the Ground Communication Section in JPL he is the Cognizant Development Engineer for the X-band portion of the transmitter described in this paper.

His previous experience includes work in the Isotope Products Laboratories (Burbank, CA) and in research institutes in Russia as a Senior Scientist in the area of low-temperature plasma, vacuum electron tubes, magneto-hydrodynamic (MHD) generators, and as a Lead Engineer for high power microwave generators, modulators, and other major assemblies for radars, particle accelerators, ion implanters, etc.

He is the author or co-author of two patents and of over 40 technical reports and journal articles, including five published in the USA.

Bruce L. Conroy has received a B.S. degree from MIT, a M.S. degree from Caltech and a J.D. degree from Loyola University of Los Angeles.

He has been employed as a microwave engineer by the Jet Propulsion Laboratory since 1967.

Arnold Silva received the B.S. degree in 1981, from the California State University at Los Angeles, California and the M.S. degree from the California State University at Northridge, California in 1987, both in electrical engineering. In 1981, he joined the Transmitter Group of ITT Gilfillan and was involved in the design of high power modulators, power converters and control circuits for the company's major radar programs. While at ITT, he was project engineer for the development of the solid-state (FET based) modulators requiring the paralleling of hundreds of FET's in a high power pulsed radar application. From 1989 to 1993, he was employed as an Engineering Specialist of Whittaker Electronic Systems engaged in the design, simulation and analysis of radar transmitter systems and subsystems, for both classified and unclassified programs. His designs have involved development of very high power, low phase noise transmitters (pulsed and CW). In 1993 he joined the Jet Propulsion Laboratory as a Member of the Technical Staff in the Transmitter Engineering Group. He has designed ultra phase and amplitude stable high-voltage power subsystems and RF subsystems for the S-band and X-band Deep Space Network (DSN) klystron-based transmitter uplinks. These systems range in power from 200W CW up to 500 KW CW X-band systems. In December of 1997, he assumed position as Group Supervisor for the Transmitter Engineering Group and oversees a team of engineers involved in multifaceted aspects and thrusts in high-power high frequency (Ka-band through W-band) transmitter technology efforts.

Gregory McDowall has been with the Jet Propulsion Laboratory since 1996, where he works in the Transmitter Engineering Group of the Communications Ground Systems Section. He is the Cognizant Development Engineer for the 20 kW PA described in this paper. He is responsible for S-band transmitter developments ranging from 200 W to 400 kW. Prior to joining JPL, he was the transmitter subsystem engineer at the Deep Space Network (DSN) Goldstone tracking facility near Barstow, CA for over fifteen years. He also served in the U.S. Navy as an Electronic Technician (Radar), Second Class.

Juan J. Ocampo received his B.S. degree in electrical engineering in 1995, and M.S. degree in Communication and Microwave Engineering in 1998 from California State Polytechnic University, Pomona, CA.

As an engineer at the Jet Propulsion Laboratory in the Communications Ground Systems Section, he is the Cognizant Development Engineer for the 20 kW transmitter discussed in this paper as well as an 800 W Ka-band transmitter to support Radio Science studies with Cassini. Previous work at JPL includes Cognizant Development Engineer for the 20 kW S-Band Beam Waveguide transmitters and design engineer for an X-Band QPSK modulator for spacecraft communications applications.